EVALUATION OF CACC VEHICLES CLUSTERING ON FREEWAY PERFORMANCE

A Thesis

by

APOORBA BIBEKA

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Yunlong Zhang
Committee Members,	Alireza Talebpour
	Kiavash Kianfar
Head of Department,	Robin Autenrieth

August 2016

Major Subject: Civil Engineering

ABSTRACT

Vehicle clustering strategy can harness the full potential of cooperative adaptive cruise control (CACC). Vehicle clustering involves finding nearby CACC equipped vehicles and forming a close spaced platoon with them if certain criteria are met. The aim of this research is to come up with a vehicle clustering strategy and evaluate the impact of this strategy on freeway performance measures such as throughput and emissions. VISSIM is used to simulate CACC equipped vehicles. Only CACC equipped trucks were modelled as one of the main focus of this research was to evaluate emission benefits of CACC system and emission benefits of platooning are more for vehicles with large frontal area. VISSIM's external driver model application programming interface (API) is used to code the driver model and vehicle clustering strategy for CACC equipped vehicles. The author developed lane change logics and platooning logics for CACC equipped vehicles. VISSIM external driver model API calculated and sent the values of control related parameters such as acceleration to VISSIM at each time step and for all the CACC equipped vehicles in the network. The author evaluated the impact of volume, market penetration rate of CACC, wireless communication, lane restriction policy and desired gap for vehicles in platoon on freeway performance. A regression model was fitted to predict the percent reduction in CO_2 based on factors such percent of time spent as a follower in platoon, desired gap and lane restriction policy.

The study showed that a dedicated lane for CACC equipped vehicles increases the throughput. In addition, there is a reduction in emissions as compared to the case when vehicles are free to choose a lane. Also, a higher market penetration rate improves

emission benefits. It was also seen that good communication between CACC equipped vehicles increases average speed.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Zhang, and my committee members, Dr. Alireza, and Dr. Kianfar, for their guidance.

I am grateful to Dr. Praprut for his guidance and support throughout the course of this research. His help was invaluable in the successful completion of this thesis.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to the Texas Transportation Institute, which provided me with the tools to carry out this research.

Finally, thanks to my mother and father for their encouragement and love.

NOMENCLATURE

ACC	Adaptive Cruise Control
API	Application Programming Interface
CACC	Cooperative Adaptive Cruise Control
CV	Connected Vehicle
DSRC	Dedicated Short Range Communication
MPR	Market Penetration Rate

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1 INTRODUCTION

Advancement in the field of wireless communication has made it possible to exchange information between moving vehicles (V2V) and vehicles and infrastructure (V2I). Moreover, auto manufacturers are coming up with vehicles which can utilizes the information from surrounding vehicles and infrastructure to give out warnings and takeover control and guidance task from the drivers. The control system, which takes over control and guidance task, is called ACC (Adaptive cruise control). Control system that takes care of longitudinal control by using information from preceding vehicles in addition to on vehicles sensor is called CACC (Control adaptive cruise control). Basically, CACC equipped vehicles in addition to the adaptive cruise control (ACC) features, have a dedicated short range wireless communication device (DSRC) which is used for local area connectivity. DSRC has an effective range of 1000 feet and a low latency of 200 microseconds (*1*). This device sends and receives information such as instantaneous acceleration, current speed and current location between the connected vehicles. CACC system processes the information from surrounding vehicles to set the appropriate acceleration or deceleration for the current time step.

CACC offers a significant improvement over adaptive cruise control (ACC) when it comes to roadway capacity. Recent studies have found that ACC vehicles might not be beneficial in improving the overall capacity and traffic stability of the roadways. Milanes et al(*2*,*3*) simulated ACC equipped vehicles and manual vehicles and found that the increase in MPR of ACC equipped vehicles had little effect on the capacity. ACC equipped vehicles use sensors to obtain data for longitudinal control thus can obtain information only from the vehicles immediately in front of them. This leads to instability when an ACC equipped vehicles is moving in a platoon. To prevent crashes and improve driver comfort ACC equipped vehicles need to maintain a large headway that is similar to manual driving.

CACC equipped vehicles offers an unparalleled advantage when it comes to traffic stability as compared to ACC equipped vehicles. This can be attributed to CACC equipped vehicles ability to obtain information regarding vehicle control from not just the immediate predecessor but also from vehicles that are present downstream and have connected vehicle technology and are within the range of the ego vehicle. Thus CACC vehicles control laws, factors in the speed and deceleration of subsequent vehicles when deciding on its speed. This results in better traffic stability which ACC equipped vehicles cannot offer.

To harness the full potential of CACC technology for improving freeway performance, vehicle clustering(*4*) is required. Vehicle clustering is when CACC equipped vehicles form a platoon. These platoons can maintain small gaps (0.6 sec) between the vehicles thus greatly enhancing the freeway capacity. Also, the vehicles in platoon have smooth acceleration thus improving traffic stability.

1.1 Problem Statement

Majority of the research on CACC equipped vehicles shows that there would be an improvement in freeway performance due to connected vehicle technology. However, connected vehicles technology offers a wide range of setting that can impact freeway performance. Thus it is important to explore further the various configurations possible with connected vehicles. Specifically, evaluating vehicle-clustering strategy is necessary to come up with clustering strategies that can be implemented in the future. The aim of this research is to develop a cluster formation algorithm to use in conjunction with a driver model for CACC equipped vehicles and quantify some of the benefits that can be obtained from it. Also, this research aims at finding the key factors with respect to CACC-equipped vehicles that would influence freeway performance measures such as freeway capacity, traffic stability and emissions.

After developing a vehicle clustering strategy, relevant comparisons can be made at different levels of factors affecting different freeway performance measures. Also, most of the research so far has focused on the car following models only and have considered a single lane freeway thus ignoring the lane changing part. Even though CACC system currently only handles longitudinal control, connected vehicles can give drivers the option to change lane to join a CACC platoon. This study incorporates the lane change logics along with car following model and vehicle clustering strategy to obtain results that are pertinent to the real world scenario. In this study the focus is on uninterrupted flow.

1.2 Research Objective

The primary goal of this research is to find out the impact of ad-hoc vehicle clustering strategy on freeway performance. Various factors such as market penetration rate, quality of wireless communication and freeway volume are evaluated. The impact of each of these factors on different freeway performance measures is estimated. The research objectives are:

- To find a suitable driver model for CACC equipped vehicles and implement it in VISSIM using driver model API.
- To develop a vehicle clustering strategy and implement it in VISSIM using the driver model API.
- To develop and implement a lane change model for CACC equipped vehicles.
- To analyze the effect of volume, market penetration rate of CACC equipped vehicles, wireless communication quality, lane management strategies such as diverting all CACC equipped vehicles on a separate lane on throughput and environment.

1.3 Thesis Organization

This thesis consists of seven Sections. Section 1 is composed of background of CACC equipped vehicles, problem statement and research objective.

Section 2 presents the details about driver model for CACC-equipped vehicles, previous research on vehicle clustering strategy. It also provides literature on the impact of CACC equipped vehicles on freeway performance.

Section 3 presents an overview of VISSIM's driver model API and lists the functions that can be performed using this module. It also describes the car following model, lane change model and platoon formation model for CACC equipped vehicles.

Section 4 describes the emission rate calculation framework. It describes how MOVES was used to estimate the emission rate. It also explains the wind drag reduction factor calculation.

Section 5 gives detail about the basic experimental setup of this study, assumption that are made, aspects of CACC that are incorporated in the analysis, scenarios that are analyzed, factors that play a key role in freeway performance with respect to connected vehicle technology, levels of factors that are chosen to carry out the analysis and the data collection process.

Section 6 present results of this research. The results include quantifying the impact of CACC equipped vehicles on freeway capacity and environment.

Section 7 summarizes the results of this research, list outs the limitation of this research and need of future work.

2 LITERATURE REVIEW

CACC is an application of connected vehicle technology which is a major field of research. It would affect almost all aspects of freeway performance such as safety, capacity, traffic stability and environmental health thus it is important of have a good understanding of this technology. We have already discussed the mechanism of CACC in the first section thus in this section, we will overview different driver models for modelling CACC. Next we would go over different vehicle clustering strategies. Finally, we would present literature on the impact of CACC on freeway performance.

2.1 Driver Model

A wide range of driver models have been developed by the researchers to model the car following and lane changing behavior of ACC and CACC vehicles. In the following paragraph the author is going to shed light some on these models.

Intelligent driver model (IDM) by Treiber et al(*5*) has been modified by the researchers for application on ACC and CACC equipped vehicles. The IDM model consists of seven parameters; desired velocity, safe time headway, maximum acceleration, desired deceleration, acceleration exponent, jams density and vehicle length. These parameters are used to estimate the acceleration at each time step. In this model the acceleration is a function of vehicle velocity, gap and velocity difference with the preceding vehicle. Eq 1 is the IDM car following model.

$$\dot{v_a} = a^{(\alpha)}\left[1 - \left(\frac{v_\alpha}{v_0^\alpha}\right)^\delta - \left(\frac{s*(v_\alpha, \Delta v_\alpha)}{s_\alpha}\right)^2\right] \quad \text{Eq 1}$$

$$s*(v_\alpha, \Delta v_\alpha) = s_0^\alpha + s_1^\alpha \sqrt{\frac{v}{v_0^\alpha}} + T^\alpha v + \frac{v\Delta v}{2\sqrt{a^{(\alpha)} b^{(\alpha)}}}$$

Where

$\dot{v_a}$ = Acceleration

$v_0 = Desired\ velocity$

T= Safe time headway

a= Maximum acceleration

b= desired deceleration

δ=Acceleration exponent

s_0=Jam distance

s_1=Jam distance

The first term in Eq 1 is for acceleration and second term is for deceleration. Thus this equation will provide acceleration when vehicle is on free road and deceleration when the ego vehicle is approaching other vehicle. The deceleration term depends on the ratio of desired and critical gap and varies with velocity and approach rate. In equilibrium traffic this model provides acceleration values such that the ego vehicle keeps a velocity dependent gap with the preceding vehicle. In low traffic density the acceleration values are similar to the acceleration values when driving on free road. In case of high approach rate this model has the capability to differentiate between emergency and normal braking. In case of emergency situation this model is designed such that there would be no collision. It considers the overreaction by drivers in emergency situations. It also models the tendency of drivers to maintain small gaps with small velocity difference with preceding vehicle. After analysis it was found that the stability results from model were similar to other distinguished model of that time.

Kesting et al(*6*) have modified the IDM by Treiber et al(*5*) so as to model ACC equipped vehicles and also to overcome the shortcoming of the IDM model. IDM model to prevent collision over estimates the deceleration due to which the model gives unrealistic values of deceleration. This phenomenon is prominent in situations involving cut in maneuvers by vehicles. To prevent this phenomenon, the IDM needs an upper limit for safe deceleration. Enhanced IDM factors in the above-mentioned shortcoming and thus provide deceleration values that are realistic. To have a safe deceleration enhanced IDM incorporates a constant acceleration heuristics (CAH) model. In this model the driver assumes a constant acceleration from the preceding vehicle. Also, no safe headway or minimum distance is required. Driver reaction is assumed to be negligible. From the results it was seen that deceleration by CAH model is significantly less negative as compared to the IDM model. However, this model fails to model the acceleration of ACC vehicles thus CAH model is used in combination with IDM model to form the enhanced IDM model. Equation 2 provides the equation for enhanced IDM model.

$a_{ACC} = a_{IDM} \; for \; a_{ACC} > a_{IDM}$

or $a_{ACC} = (1-c)a_{IDM} + c\left[a_{CAH} + b\tanh\left(\frac{a_{IDM}-a_{CAH}}{b}\right)\right]$ otherwise Eq 2

Vanderwerf et al(*7*) investigated the different driving models and found the ones which can closely simulated the behavior of humans while driving conventional vehicles and the behavior of vehicles equipped with ACC and CACC. Default driver behavior models that are used in most traffic simulation and modeling tools are inadequate to model the interactions between vehicles when connected vehicles are present. To factor in the interactions, the authors went through the existing literature to find the models that can be implemented for conventional human driven vehicles, vehicles with ACC and CACC with and without cooperating preceding vehicle. Acceleration and deceleration limits of 2 and -2 m/s^2 were assumed to have comfortable acceleration and braking. Vehicle velocity was considered to be less than the desired velocity. Following is the error based control law followed by the authors:

u"2" (t)=-k"f"[x ̇"2" (t)-v"2d"(t)]

Where

kf = 0.4,

x ̇"2" (t)= speed of following vehicle

v"2d"(t)=desired speed of second vehicle

u"2" (t)= Acceleration of the second vehicle

A first order lag was considered between controller command u and vehicle response a

a ́=(u-a)/Tc

The authors used a driver model by Song and Delrme for human driven vehicles as it had more room for tuning and incorporated recent research on perceptions. To model the ACC equipped vehicles they modified the car following model by godbole for ACC equipped vehicles. The basic concept of this model is to maintain a safe distance from the preceding vehicle. CACC model is a modification of ACC model. The authors only considered the communication between vehicles on the same lane to simplify the analysis. After running the analysis, it was found that the increase in capacity due to CACC equipped vehicles was almost twice that of ACC equipped vehicles on manually driven vehicles.

Van Arem et al(*8*) analyzed the effect of CACC on traffic flow using MIXIC traffic flow simulation model. To study CACC's impact on traffic flow the authors added a component to handle CACC situation. Similar to ACC component of MIXIC the CACC component takes over a part of the longitudinal model of MIXIC. CACC model calculates reference acceleration for the ego vehicle based on the data obtained from predecessor vehicle.

The driver model in conjunction with vehicle model calculates the coordinates of vehicles at every time steps. Like most micro simulation model it has a lane change model and a longitudinal model that helps determine the lateral and longitudinal position of a vehicle. In addition to these standard model MIXIC has model for ACC i.e. when vehicles are running on ACC a part of longitudinal model is controlled the ACC component of MIXIC.

The car following model of MIXIC(*9*) has two driving behavior. While driving is uncongested traffic condition free driving behavior is employed in which the driver tries to maintain or reach his/her intended speed. And in congested traffic conditions car following behavior is employed in which the follower adjusts his speed and/or following distance so that he/she can maintain a desired clearance between the predecessor vehicle and themselves.

Furthermore, MIXIC has two models to determine a vehicles action with respect to longitudinal movement. One is a driver model that evaluates the drivers desired acceleration based on the current conditions. Second is vehicle model that takes into account vehicles current state. Vehicle model consists of parameters for things such as accelerator pedal position, gear position and force on break pedal. The driver model in conjunction with vehicle model determines the actual acceleration of the vehicle.

In situations where there is no traffic ahead for a long distance, the free driving behavior of the driver model is employed. The model compares the current speed with the desired speed and if deviates more than a given proportion from desired speed than desired acceleration is made proportional to the speed error taking into account the reaction time of driver.

In the car following behavior the driver estimates the speed of the lead vehicle and tries to maintain a relative speed of zero and a desired clearance with the lead vehicle. The relative speed component was added to the original model to increase traffic flow stability. Desired acceleration is calculated by taking into account the above parameters. A perception threshold is determined so as to prevent vehicles from reacting to lead vehicles that are far ahead. Driver's reaction time and foot position with respect to brake accelerator are also modeled to arrive at a realistic model.

Shladover et al(*10*) evaluated the impact of ACC and CACC market penetration rate on freeway capacity. The authors determined the freeway capacity by AIMSUN (microscopic and mesoscopic simulation software). In this study the authors only considered a one-lane freeway so lane change model utilized. Manual, ACC, Here I am and CACC vehicles were simulated. For the car following model the authors used simplified control laws obtained from the control logic implemented in a field test done by the authors(*3*). Two-control settings were modeled for ACC/ CACC equipped vehicles. First one is speed control setting and second in gap control setting. Speed control was activated when the spacing of the leader was more than 120 meters and gap control is activated when the spacing is smaller than 100 meters. "If the spacing is between 100 m and 120 m the vehicle follows the previous time step control setting. "In speed control the control law is" (*10*).

"In speed control the control law is" (*3*)

$$v_e = v - v_d$$

$$a_{sc} = bound(-0.4 * v_e, 2, -2)$$

$$a = a_{sc}$$

$$bound(x, x_{ub}, x_{lb}) = \max(\min(x, x_{ub}), x_{lb})$$

2 and -2 and maximum and minimum acceleration in m/s^2

In gap control the control law is

$v_e = v - v_d$

$a_{sc} = bound(-0.4 * v_e, 2, -2)$

$s_d = T_d.v$

$s_e = s - s_d$

$a = bound(\dot{s} + 0.25.s_e, a_{sc}, -2)$

where

$v =$ speed of controlled ACC/CACC vehicle (m/s),

$v_d =$ desired speed set by driver or speed limit of road (m/s),

$v_e =$ speed error (m/s),

$a_{sc} =$ acceleration by speed control (m/s^2),

$s =$ spacing between controlled vehicle and its leading vehicle (m),

$s_d =$ desired spacing (m),

$s_e =$ spacing error (m), and

T_d=desired time gap (s).

After running the simulation for varying market penetration rate for different vehicle type it was found that the when only ACC equipped vehicles and manual vehicles were simulated the increase in MPR of ACC equipped vehicles had a very little effect on the capacity. This was attributed to similarities between manual driving and driving behavior of ACC equipped vehicles. For CACC vehicles as the MPR rate increased the capacity also increased. The maximum capacity obtained was around 4000 vehicles/hour. It was also found that Here I am vehicles help in further increasing the capacity of highways at lower MPR of CACC vehicles.

There are different driver models for CACC equipped vehicles. These model are based on different requirements. These model can be divided into two broad categories; one type of model requires the vehicle to maintain a desired time gap and the second category of models requires the vehicles to maintain a desired distance when following another vehicle. Kesting et al. (*6*) and Shladover et al. (*10*) driver models are time based models. Vanderwerf et al(*7*) and Van Arem et al(*8*) driver models are distance based driver models. All of the driver models put an upper and lower bound on acceleration so as to provide a stable ride.

2.2 Vehicle Clustering Strategy

There are different types of vehicle clustering strategies that can be implemented on CACC equipped vehicles. Although researchers have done extensive work regarding the coupling of heavy duty vehicles, there is a dearth of research on vehicle clustering of CACC equipped vehicles.

Shladover et al (*4*) have pointed towards some of the strategies that can be implemented for vehicle clustering. First, the authors talk about ad hoc clustering in which “vehicles arrive in random sequence and do not deliberately seek out other similarly equipped vehicle”. In this strategy the chances of forming a platoon is directly proportional to the MPR of connected vehicles. Second strategy is local coordination. This strategy required CACC equipped vehicles to search for other CACC equipped vehicles and speed up or down or change lanes to form platoon. A major limitation of this strategy is that it is hard to determine the current lane of a vehicle accurately. To overcome this problem, innovative ways of lane determination such as driver confirmation, unique lane marking or “vehicle based confirmation” using infrared camera-visible marking needs to be implemented. A third strategy that the authors mentioned is called global coordination. It involved platooning vehicles based on similar origin and destination pairs. This strategy can be implemented in various ways. For instance, “vehicles are grouped before entering the highway”. One drawback of this strategy is that vehicles might need to wait for several minutes before they could find an equipped vehicle with same O-D.

2.3 CACC Impact on Freeway Performance*

During the past few decades several researchers have worked on CACC technology and tried to quantify the effect of CACC vehicles on freeway performance measures such as capacity, emissions and traffic stability. Many of the studies are promising and show that at high market penetration rates CACC equipped vehicles can have a positive effect on freeway performance.

Increase in traffic has put immense pressure on the existing infrastructure. There is need for roadway widening at many corridors in USA but not enough resources. To address this situation, researchers have come up with CACC. CACC technology has the potential to drastically increase freeway capacity and traffic stability.

*Reprinted from Songchitruksa, P., A. Bibeka, L. Lin, and Y. Zhang. Incorporating Driver Behaviors into Connected and Automated Vehicle Simulation. Report ATLAS-2016-13, Advancing Transportation Leadership and Safety (ATLAS), 2016.

2.3.1 CACC Impact on Freeway Operations

Vanderwerf et al. (*7*) after develpoing a car following model for the ACC and CACC equipped vehicles perfomed monte carlo simulation to estimate the affect of different vehicle types on the freeway capacity. For 100% MPR the authors founnd that the freeway capacity was 2050, 2200 and 4500 vehicles/hours for manual driving, ACC and CACC respectively. It was seen that CACC significantly increases the capacity as compared to other two. The lack of increase in capacity in ACC case was attributed to the fact that ACC equipped vehicles take decision based on sensor data which is error prone thus a platoon of ACC vehicles is not string stable and has to maintain a longer distance as compared to CACC platoons which are string stable.

Milanes et al. (*3*) got similar results as Vanderwerf et al. (*7*). After running the simulation for varying market penetration rate for different vehicle type the authors found that the when only ACC equipped vehicles and manual vehicles were simulated the increase in MPR of ACC equipped vehicles had a very little effect on the capacity. This was attributed to similarities between manual driving and driving behavior of ACC equipped vehicles. For CACC vehicles as the MPR rate increased the capacity also increased. The maximum capacity obtained was around 4000 vehicles/hour. It was also found that Here I am vehicles help in further increasing the capacity of highways at lower MPR of CACC vehicles.

Van Arem et al. (*8*) checked the impact of CACC equipped vehicles on stability by considering a platoon of 4 vehicles approaching a predecessor vehicle. Different market penetration rates were tested. It was found that CACC at 100% MPR were able to maintain a smaller gap and the platoon acceleration and decelartion was smoother as compared to the referene case with only manual driver vehicles. The authors than evaluated the impact of CACC on traffic flow at different MPR. They found that throughput does not change much at MPR less than 40%. To have benefits on traffic stability and throughput the MPR should be greater than 60%.

Kesting et al. (*6*) found a linear increase in capacity as the percent of ACC increased by one percent. This results is according to Milanes et al. (*3*) might not be representative of real world scenarios as in actual field tests it has been seen that there is a reduction in capacity when ACC equipped vehicles are tested.

There is a body of literature that shows that CACC would for sure increase the freeway traffic capacity and stability. Conflict of opinions comes when evaluating the impact of ACC vehicles on freeway capacity. Some have shown ACC equipped vehicles will improve capacity whereas others have shown it to be no better than the manual driving. However as more and field test are being conducted it is becoming evident that ACC would have little or no impact on capacity.

2.3.2 CACC Impact on Fuel Consumption and Emissions

CACC equipped vehicles can maintain smaller gaps as compared to manual driving. So when CACC equipped heavy vehicles move in a platoon they experience wind drag reduction, which translates to reduction in overall power that a vehicle has to exert to maintain the same speed or accelerate. This reduces the fuel consumption and the tailpipe emissions.

Alam et al. (*11*) evaluated platoons formed by HGV equipped with ACC. They added a feature so as to allow the following vehicle to obtain the information of traffic conditions ahead of lead vehicle. This feature is similar to the CACC framework and thus the experimental results can be extrapolated for CACC equipped vehicles. The authors showed that due to close following and reduction in wind drag a reduction in fuel consumption between 4.7 to 7.7% can be obtained. Also the authors found that reduction in fuel consumption is affected by the weight of the leading truck. A heavier lead truck will result in lower fuel consumption as compared to lighter truck. The authors also found that a smaller gap results in lower fuel consumption, and this was because the wind drag reduces as the clearance between the vehicles in a platoon reduces.

Bonnet et al (*12*) used an electronic tow bar to allow two heavy vehicles to move at a close spacing. The lead vehicle was driven manually and the follwing vehicle had a controller to follow the leader automatically. The author ran a series of experiments at different speed and spacing combinations with the highest spacing being 16 meters. The authors found a reduciton in fuel consumption at all the levels. It was seen that the reduciton in fuel saving increases with decrease in clearance but reduction reaches a plateau at a clearance of 10 meters. Thus a 10 meter clearnace is optimal for fuel saving. A fuel saving between 5 to 10 percent was observed in this study.

Tsugawa et al. (*13*) coducted a study to evaluate platooning with respect to three CACC equipped heavy vehicles and found similar results as above two papers. The authors focussed on the impact on emission and energy consuption due to close following and found a 2.1 % reduction in CO_2 at a spacing of 10 m and 40% market peneteration rate.

There have been a lot of studies similar to the above mentioned studies and almost all have shown CACC will have a positive impact on fuel consuption and emissions. A common conclusion that can be make from above studies is that with closer spacing there would be an increase in fuel consumption reduction and emission reduction. Futhermore a distance of 10 meters might be the optimal clearance setting.

3 DRIVER AND PLATOONING MODELS*

To model CACC equipped vehicles the author replaced several component of driver model. VISSIM's external driver model API was used to code the models for CACC equipped vehicles. As existing car following model from the literature was used with small variation. Next, the author came up with different lane change logics for the CACC equipped vehicles. The author also developed a platooning algorithm for CACC equipped vehicles. In order to promote platooning special lane change logic for CACC equipped vehicles during platooning were developed. In this section we would be discussing the following topics in detail:

- VISSIM External Driver Model API
- Car Following Model
- Lane Changing Model
- Platooning Model

3.1 VISSIM External Driver Model API

External driver model API is an application programming interface which has the capabilities of changing the existing driver model of VISSIM. It can also be used to extract performance measures thus it is an apt tool for modeling and analyzing CACC equipped vehicles. The interface is written in C++. Variables such as desired speed, current speed, current acceleration, spacing from the leader, target lane can be obtained for the ego vehicles. Also, data for two vehicles upstream and downstream and same

*Reprinted from Songchitruksa, P., A. Bibeka, L. Lin, and Y. Zhang. Incorporating Driver Behaviors into Connected and Automated Vehicle Simulation. Report *ATLAS-2016-13*, *Advancing Transportation Leadership and Safety (ATLAS)*, 2016.

lane and two lanes on both sides of the ego vehicle can be obtained. The adjacent vehicles have two identifying numbers associated with them. One number helps to find out whether the vehicle is upstream or downstream. The second number is to find out the adjacent vehicle's lane. Different variables can be extracted for the adjacent vehicles. These include speed, lane position, and spacing from the ego vehicle. VISSIM puts a visibility distance after which an adjacent vehicle is not visible that is the information regarding the adjacent vehicle is not obtained by the ego vehicle. This limit is 800 feet.

The DLL has four commands:

- INIT – The initialization command is called when the simulation run starts. This command is called only once. Objects which need to be created only once and which would be used throughout the simulation can be created under this function. This function can also be used to provide path for input and output files.
- CREATE – This command is called when a new vehicle is inserted into the network. This is the location where the piece of code to hold information pertaining to a particular vehicle should be implemented. This command can be called multiple times during a time step.
- MOVE – The command is called at every time step for every vehicle that is present in the network. This command is where different driver model and other relevant factors can be modified. This is the only command that is called at every time step so this is a very powerful command. It can be

used to send acceleration values, target lane values and other values critical for vehicle control to VISSIM. One thing to keep in mind while using this command is that it is called multiple time during every time

- step depending on number of vehicles in the network. So if a user wants to call a function only once per time step he/she needs to write their code appropriately so that the function is called only once per time step and not for every vehicle for each and every time step. This command is also useful for adding codes for extracting the performance measures.
- KILL – This command is called whenever a vehicles exit a network. This command is also called when the simulation ends in order to remove all the vehicles from the network. This command provides the user with the power to keep track of vehicles in network and of those which have left the network.

Driver model DLL also offers the user two options to carry out the lane change. One is called the simple lane change. In this type of lane change the user just specifies the target lane of the ego vehicle and VISSIM takes care of the entire lane change process. During this lane change VISSIM does not take suggestion from the user. The second type of lane change gives more power to the user. In this type of lane change the user has the ability to control the entire lane change process. This includes specifying the angle at which the ego vehicle should initiate the lane change, the criteria to stop lane change and other control related parameters. The user need to specify the target lane and position in the target lane after reaching which the ego vehicle will stop the lane change process.

3.2 Car Following Model

The car following model is responsible for the longitudinal control of the vehicles. It provides acceleration for every time step. In this study the driver model by Milanes et al. (*2*,*14*) is used. The authors have addressed the short comings of various previous car following models for CACC-equipped vehicles. Also, unlike other previous models, this model was validated with field data.

This model basically has two modes. One is speed control mode and the other one is gap control mode. Speed control mode is activated when the car is in free flow and there is no leader or the leader is more than 120 meters from the ego vehicle. This mode is to address situations when an ego vehicle has no immediate leader. In this mode the objective of the ego vehicle is to reach its desired speed. The second mode is gap control mode. This mode is activated when the distance between the ego vehicle and the leader is less than 100 meters. This gap control mode is activated in close following situations and in this mode the ego vehicle takes into account the spacing between it and the lead vehicle, their relative speed to take control decisions. To prevent rapid switching between the two modes, a buffer zone (100 to 120 meters) is provided. When the spacing between ego and lead vehicle is between 100 and 120 meters, the vehicles use the control mode from the previous time step.

Since different drivers would have different preferred time gaps, the CACC equipped vehicles are assigned a desired time gap based on random number generated from a normal distribution with a mean of 2 seconds and a standard deviation of 0.4 seconds.

The deceleration limit of the original mode (-2 m/s^2) was replaced with a lower limit (-3.4 m/s^2) so the CACC equipped vehicles were able to handle sudden stop conditions.

Figure **1** presents the flowchart of the algorithm that was used in the driver model API. This algorithm was invoked at each time step (0.1 seconds) for every CACC equipped vehicle in the network to calculate the acceleration for that time step.

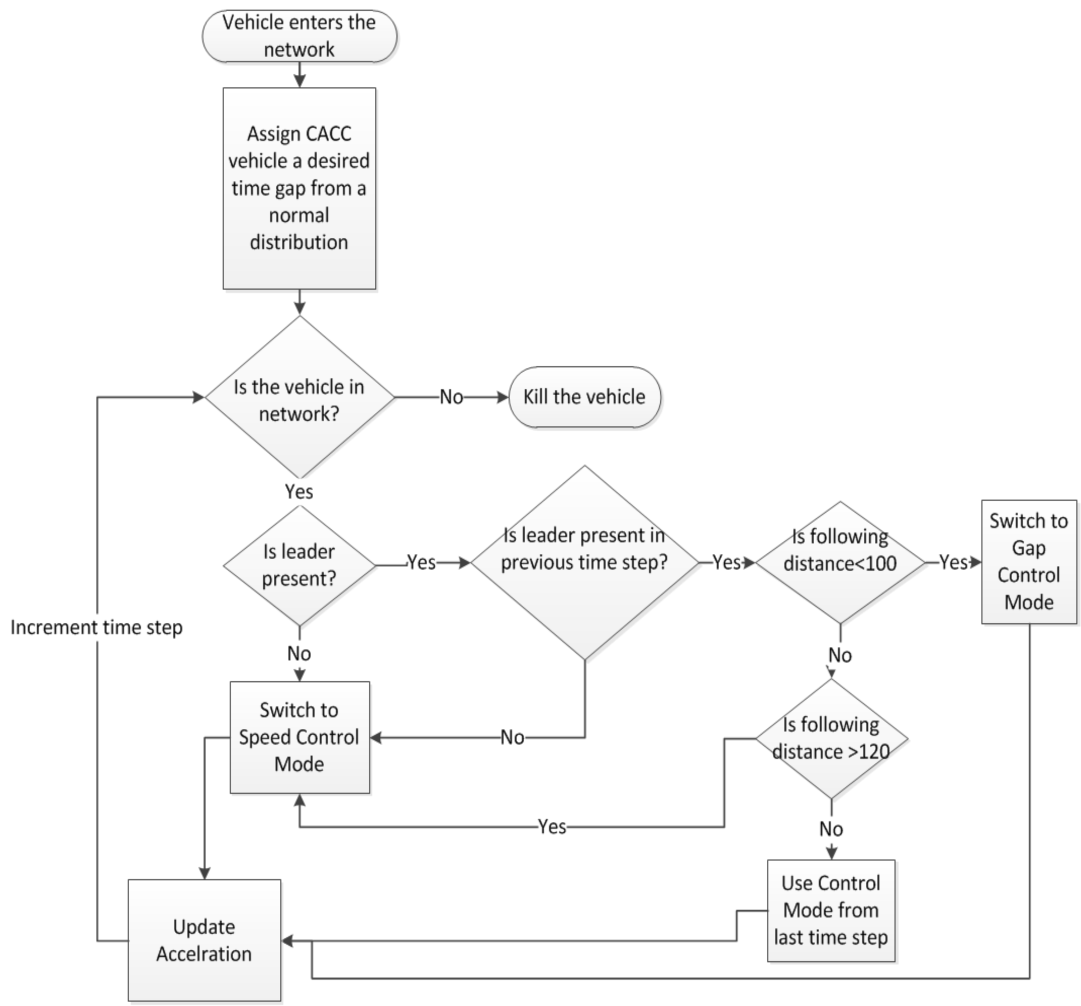

Figure 1: A Car Following Logic for CACC Simulation (*15*).

3.3 Lane Changing Model

A lane change model was added to the CACC equipped vehicles. The main objective of this lane change model was to promote platoon formation. A CACC equipped vehicle looks out for nearby equipped vehicles. If there is an equipped vehicle present and it is the immediate leader than the vehicle is forced to stay in the current lane and form a platoon. On the other hand, if a CACC equipped vehicle present in one of the adjacent lane is the immediate leader to the left or the right then the ego vehicle looks for an opportunity to change the lane. The ego vehicle checks the time gap with respect to the leader and follower in the desired lane. If the gap is sufficient for the ego vehicle to safely change its lane than it begins a lane change maneuver. Moreover, whenever a CACC equipped vehicle detects a platoon in the adjacent lanes it tries to become the last member of the platoon. It only changes lane if it could be last vehicle in the platoon. Thus the lane change is meant not to disturb the existing platoons and is designed only to promote platoon formation and minimize any potential platoon breakups.. Figure 2 shows the algorithm for the lane change model.

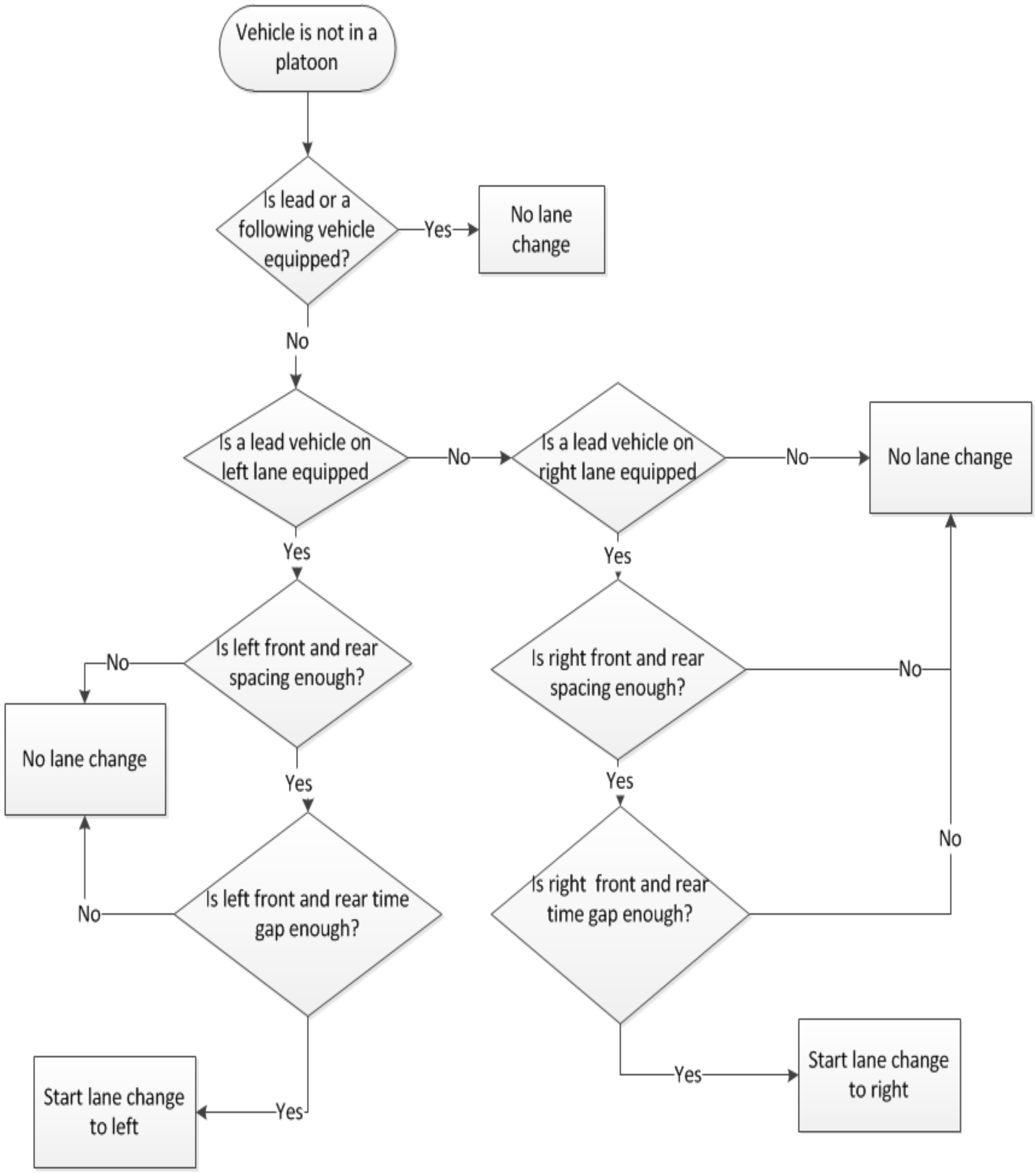

Figure 2: A Lane Changing Logic for CACC Simulation (15).

The manual driven vehicles follow the default lane change model inside VISSIM. The lane change logics when the vehicles are in a platoon are different and discussed in the next section.

3.4 Platooning Model

CACC equipped vehicles have the capability of forming tight spaced platoons. CACC equipped platoons can increase capacity, reduces emission and improves traffic stability. In order to improve platoon formation a platooning model was created. The control logic of gap control mode was modified for follower vehicles in platoon. The aim of this study is to study closed spaced platoons so in the gap control mode the objective of the subject vehicle was changed so that it accelerated or decelerated in order to reach its desired time gap. Following is the car following model used in gap control mode:

$$s_d = T_d . v$$
$$s_e = s - s_d$$
$$a = \max(\dot{s} + 0.25 s_e, -3.4)$$

where:

v = speed of controlled ACC, CACC vehicle (m/s).

s = spacing between controlled vehicle and its leading vehicle (m).

sd = desired spacing (m).

Td = desired time gap (s).

a = acceleration (m/s2).

This logic helped in creating ad hoc platoon formations. The salient features of the platooning model are:

- The distance between two CACC equipped vehicles should be less than hundred meters for them to recognize each other and start the platoon formation process.
- A CACC equipped vehicle has to follow another CACC equipped vehicle for ten seconds before forming a platoon. This duration can be changed. A ten second time window was taken to prevent vehicles from rapidly switching between platooning and non-platooning modes.
- The followers in a platoon are assigned a desired time gap. The desired gap has two levels (0.2 and 0.6 seconds).
- Following vehicles in a platoon can have a signal drop. This signal drop is based on a wireless reception model discussed in the next section.
- In case of a signal drop the following vehicle changes back to ACC driving mode or becomes the new platoon leader based on the size of the initial platoon. In non-platooning mode the driver desired time gap changes back to one before platooning.
- If the number of vehicles in a platoon is more than two, then the platoon breaks at the 3rd vehicle. Thus fixing the maximum platoon size to two.

Figure 3 shows the platooning algorithm

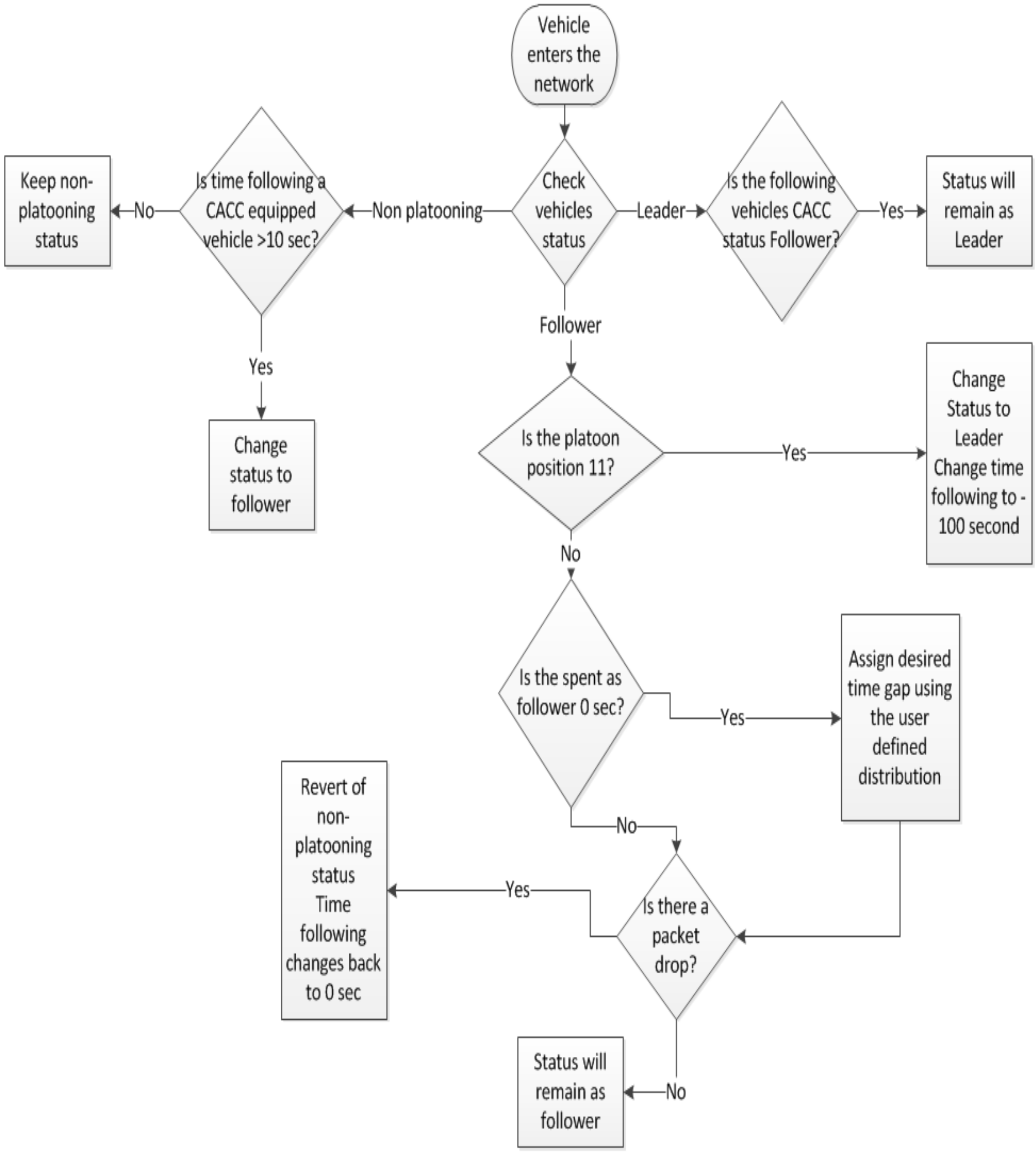

Figure 3: Platooning Algorithm (15).

3.4.1 Probabilistic Wireless Reception Model

To model wireless data reception, we implemented a probabilistic wireless reception model proposed by Killat et al. (*16*) in the API. Killat et al.'s model is based on the Nakagami distribution with m=3. The model for packet drop is based on two key parameters: crossover distance (*CR*) and distance between sender and receiver (*d*). Crossover distance is the communication range of the transmitter. Two crossover distances of 100 meters and 250 meters were selected in this study to represent poor and good wireless communication quality.

In our modeling scenarios, the vehicles join a platoon only when the distance between the ego vehicles and the potential leader is less than 100 meters, packet drop equation for cases when *d* is less than *CR* can be used. The following equation expresses the probability of receiving a packet:

$$\Pr\left(d,CR\right)=e^{-3\left(\frac{d}{CR}\right)^{2}}\left(1+3\left(\frac{d}{CR}\right)^{2}+\frac{g}{2}\left(\frac{d}{CR}\right)^{4}\right)$$

where

CR (Crossover distance) = Maximum achievable communication distance

D = Distance between the sender and the receiver

g = Gravitational coefficient

4 EMISSION CALCULATION*

To estimate the emissions, we utilized second-by-second vehicle trajectory data and following distances from the simulation. Commonly used tools such as MOVES, CMEM and VT-Micro can all be used to estimate various vehicular pollutants. We utilized the emission rates of HDV from MOVES2014 (*17*) in this study since it is the most up-to-date database publicly available. Thus, in order to estimate the emission rates for different vehicles in a timely manner, the core model from MOVES was coded into R and the trajectory files from VISSIM were post processed using R software package. Moreover, by using the emission model instead of the software, we can adjust the wind drag coefficient based on the second-by-second following distance when the vehicles are in platooning state and then estimate the emissions accordingly. Following sections discuss the emission calculation process in details.

4.1 Emission Rates

To calculate the emission rate, MOVES uses the concept of operating bins. Speed, acceleration and scaled tractive power are used to categorize different operating bins. Different operating bins have different emission rates. The total emission or emission rate for different vehicle types can be calculated using operating mode distribution for a vehicle type.

A project level scenario was analyzed. Default values were used for parameter such as fuel composition. A diesel fuel-combination long haul truck was chosen as the target

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vehicle type. To obtain the emission rate for different operating bins an operating bin distribution was entered. This distribution specified the percentage of time a vehicle travelled in a particular operating bin. To get the different emission rates for different operating bins, the operating bin distribution was coded such that different links represented different operating modes and thus emission rate for any link can be taken as the emission rate for the corresponding operating bin. Table 1 presents the emission rates obtained from the MOVES.

Table 1: Emission Rates for Different Operating Bins (15).

Operating Bin	Emission Rates (grams/mile)			
	Hydrocarbons	**CO**	**NOx**	**CO_2**
0	0.06	0.09	0.74	340.99
1	0.05	0.15	0.56	168.77
11	0.12	0.26	0.67	223.98
12	0.12	0.31	1.87	643.10
13	0.14	0.44	3.02	1160.50
14	0.15	0.53	4.26	1685.30
15	0.13	0.58	5.34	2125.49
16	0.14	0.69	6.70	2906.19
21	0.11	0.24	0.58	179.85
22	0.14	0.56	2.11	820.95
23	0.13	0.67	3.08	1350.41
24	0.13	0.73	4.43	1945.74
25	0.12	0.78	5.72	2496.49
27	0.12	0.68	7.17	3424.29
28	0.12	0.65	7.79	4794.01
29	0.15	0.83	10.01	6163.72
30	0.18	1.02	12.24	7533.43
33	0.14	0.59	2.04	727.30
35	0.12	0.71	4.50	2199.44
37	0.12	0.67	6.97	3428.05
38	0.12	0.54	8.28	4799.27
39	0.16	0.69	10.65	6170.46
40	0.19	0.85	13.02	7541.68

4.2 Scaled Tractive Power

The fraction of time each vehicle spends in different operating mode is used to determine the total emission or average emission rate. All vehicle trajectories were recorded from the simulation. This file contains second-by-second details such as simulation time, vehicle speed, vehicle acceleration and spacing. Speed and acceleration and vehicle mass were used to calculate scaled tractive power (STP). The vehicle mass was fixed at 33000 lbs. STP, speed and acceleration were then used to allocate the fraction of time a vehicle spends in different operating modes. This was then used with emission rates table to compute the average emission rate for a vehicle. The following equation shows the STP calculation.

$$STP_t = \frac{Av_t + Bv_t^{\,2} + Cv_t^{\,3} + Mv_t\left(a_t + g.sin\theta\right)}{f_{scale}}$$

where

$STP_t =$ the scaled tractive power at time t [scaled kW orskW]

A = the rolling resistance coefficient [kW-sec/m]

B = the rotational resistance coefficient [kW-sec^2/m^2]

C = the aerodynamic drag coefficient [kW-sec^3/m^3]

M = mass of individual vehicle

f_{scale} = fixed scale factor (17.1)

v_t = instantaneous vehicle velocity at time t [m/s]

a_t = instantaneious vehicle acceleration at time t [m/s^2]

g = acceleration due to gravity [9.8 m/s^2]

$sin\theta$ = fractional road grade

The A value corresponds to rolling resistance offered to the vehicle by the roadway surface. B is zero for heavy vehicles. The C value corresponds to the wind drag resistance.

$$A = 0.0661 \times M\ (M \text{ is in metric ton})$$

$$B = 0$$

$$C = 0.5 C_D \times \rho \times A_1$$

where

A_1 = Frontal area of truck (12.5 m^2)

ρ = Air density (1.225 kg/m^3)

C_D= aerodynamic drag coefficient (0.65)

4.3 Wind Drag Reduction

To model the benefits of platooning on emissions, we accounted for the wind drag reduction that a vehicle will experience when it is closely following another vehicle. To model wind drag reduction a wind drag reduction tables by Hong et al. (*18*) are used. These tables (Table 2 and Table 3) consist of wind drag reduction at different car spacing for leader and follower. This table is for spacing up to one car length however in the study by Hong et al. it was seen that there is some reduction for follower and for leader up to around two car lengths spacing. This can be observed in Figure 4. Thus the values from the table were extrapolated to get the wind drag reduction at car lengths more than one. Also wind drag reduction for missing car spacing values were estimated by interpolation.

Table 2: Wind Drag Reduction for Leader (*18*).

Car Spacing (Car Length)	**$C_D/C_{Neutral}$**
0.2344	0.6380
0.2865	0.5910
0.3802	0.6111
0.5521	0.7848
0.7448	0.8808
1	0.9541

Table 3: Wind Drag Reduction for Follower (*18*).

Car Spacing (Car Length)	**$C_D/C_{Neutral}$**
0.2344	0.7278
0.2865	0.6657
0.3802	0.6978
0.5521	0.6259
0.7448	0.6724
1	0.7379

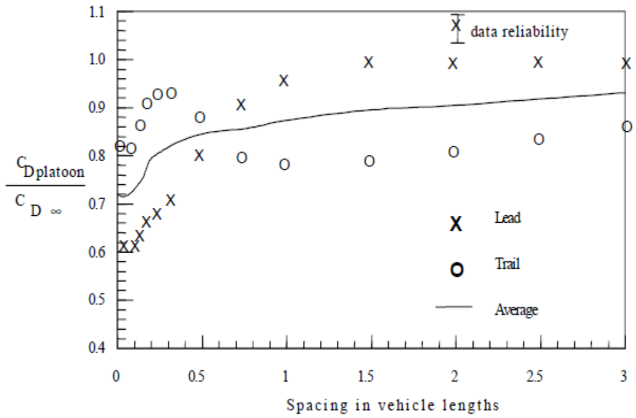

Figure 4: Reduction in Wind Drag Coefficient (*19*).

5 EXPERIMENTAL SETUP AND DATA COLLECTION*

To evaluate the effect of CACC platooning on freeway performance measure a freeway network was created. Only freeway basic section was considered that is merging was not modeled. Various factors such as quality of communication, special lane management strategies were evaluated. The factors were combined to come with different scenarios. These scenarios were used to evaluate the impact of CACC clustering on different freeway performance measures such as traffic stability, flow and emissions. In this section the focus would be on the experimental setup that was created to evaluate CACC equipped vehicles. The data collection procedure is also discussed.

5.1 Network Description

The simulation test bed is a 26-mile freeway section. The study site is approximately 26 miles. All the on and off ramps along the eastbound freeway are not used to simplify the simulation process in this study as well as to obtain accurate throughput values.

Data collection points are placed at the middle of the study freeway segment on every lane to collect speed and throughput data. Travel time is collected when each vehicle leaves the network. The speed limit of this freeway is 70 mph (113 km/h).

All the ramp traffic was set to zero for this case study in order to provide a controlled environment for quantifying direct impacts of platooning. The test section can be considered as a basic freeway section. Only CACC equipped heavy duty vehicles were considered instead of light duty vehicles. This is because heavy vehicles have bigger frontal area as compared to light vehicles and thus reduction in emission rate is more

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pronounced for heavy-duty vehicle platoon. The speed limit for heavy-duty vehicles was set at 65 mph and for light duty vehicles was set at 70 mph.

5.2 Factors Evaluated

There are various factors that can affect freeway performance measures. Some of the important factors pertaining to connected vehicle environment were evaluated to find out how each factor or combination of factors effect different freeway performance measures. Table 4 summarizes the factors that are evaluated in this study.

Table 4: Variables and Levels Evaluated in the Simulation Study (15).

Factors	Levels	Comments
Volume (Vehicle/Hour)	2500 and 4000	This represents low and high volumes.
Market Penetration Rate CACC (%)	10, 30, 50 and 70	All the connected vehicles are assumed to be HDV.
Transmission Power (meter)	100 and 250	Transmission power is the range of DSRC.
Gap Setting	• 0.2 Seconds • 0.6 Seconds	Desired gap is the time gap which a vehicle wants to maintain with its lead vehicle.
Lane Control Setting	• CACC Left Lane • Free Lane Selection	All CACC equipped vehicles are in left lane in CACC left lane setting.

Below describes the consideration of the levels used in each factor:

- Traffic Volume – Traffic volume levels represent the opportunity for CACC equipped vehicles to form platoons.
- Market Penetration Rate of CACC – The 10% level represents the near future scenarios and higher values represent future scenarios when more and connected vehicles are on the roadways. A maximum market penetration rate of seventy percent was used because it is very time consuming to run VISSIM at higher market penetration rate.
- Transmission Power – The high and low transmission power represent the good and poor wireless communication quality. The probability of wireless reception depends on the distance between a pair of connected vehicles. The increase in the distance will reduce the reception probability.
- Gap Setting – A platoon can have different gap settings. In this study two gap setting (0.2 and 0.6 seconds) are analyzed. At 65 Mph 0.2 and 0.6 seconds gap setting represents spacing of around 18 and 57 feet respectively.
- Lane Control Setting –Lane selection setting restricts a platoon to change lane once it is formed. This is done to preserve a platoon for as long as possible. The second setting restricted all the CACC equipped vehicles on the left lane. Manual driven vehicles were free to on any lane. This lane

setting promotes platoon formation. Longer and more stable platoons are expected from this setting.

- Maximum Platoon Length – There can be restriction on the platoon size based on factors such as safety, stability and environment benefits. In this study three settings of maximum platoon length are evaluated.

Using different combinations of these factors a total of 60 scenarios were created. Table 5 presents the list of these scenarios.

Table 5: List of Scenarios.

Scenario	Volume	Lane Control Setting	Desired Gap (seconds)	MPR of CACC	Transmission power (meters)
1	4000	CACC Left Lane	0.2	10	100
2	4000	CACC Left Lane	0.2	10	250
3	4000	CACC Left Lane	0.2	30	100
4	4000	CACC Left Lane	0.2	30	250
5	4000	CACC Left Lane	0.2	50	100
6	4000	CACC Left Lane	0.2	50	250
7	4000	CACC Left Lane	0.6	10	100
8	4000	CACC Left Lane	0.6	10	250
9	4000	CACC Left Lane	0.6	30	100
10	4000	CACC Left Lane	0.6	30	250
11	4000	CACC Left Lane	0.6	50	100
12	4000	CACC Left Lane	0.6	50	250
13	4000	Free Lane Selection	0.2	10	100
14	4000	Free Lane Selection	0.2	10	250
15	4000	Free Lane Selection	0.2	30	100
16	4000	Free Lane Selection	0.2	30	250
17	4000	Free Lane Selection	0.2	50	100
18	4000	Free Lane Selection	0.2	50	250
19	4000	Free Lane Selection	0.2	70	100
20	4000	Free Lane Selection	0.2	70	250
21	4000	Free Lane Selection	0.6	10	100
22	4000	Free Lane Selection	0.6	10	250

Table 5: Continued.

Scenario	Volume	Lane Control Setting	Desired Gap (seconds)	MPR of CACC	Transmission power (meters)
23	4000	Free Lane Selection	0.6	30	100
24	4000	Free Lane Selection	0.6	30	250
25	4000	Free Lane Selection	0.6	50	100
26	4000	Free Lane Selection	0.6	50	250
27	4000	Free Lane Selection	0.6	70	100
28	4000	Free Lane Selection	0.6	70	250
29	2500	CACC Left Lane	0.2	10	100
30	2500	CACC Left Lane	0.2	10	250
31	2500	CACC Left Lane	0.2	30	100
32	2500	CACC Left Lane	0.2	30	250
33	2500	CACC Left Lane	0.2	50	100
34	2500	CACC Left Lane	0.2	50	250
35	2500	CACC Left Lane	0.2	70	100
36	2500	CACC Left Lane	0.2	70	250
37	2500	CACC Left Lane	0.6	10	100
38	2500	CACC Left Lane	0.6	10	250
39	2500	CACC Left Lane	0.6	30	100
40	2500	CACC Left Lane	0.6	30	250
41	2500	CACC Left Lane	0.6	50	100
42	2500	CACC Left Lane	0.6	50	250
43	2500	CACC Left Lane	0.6	70	100
44	2500	CACC Left Lane	0.6	70	250
45	2500	Free Lane Selection	0.2	10	100
46	2500	Free Lane Selection	0.2	10	250
47	2500	Free Lane Selection	0.2	30	100
48	2500	Free Lane Selection	0.2	30	250
49	2500	Free Lane Selection	0.2	50	100
50	2500	Free Lane Selection	0.2	50	250
51	2500	Free Lane Selection	0.2	70	100
52	2500	Free Lane Selection	0.2	70	250
53	2500	Free Lane Selection	0.6	10	100
54	2500	Free Lane Selection	0.6	10	250
55	2500	Free Lane Selection	0.6	30	100
56	2500	Free Lane Selection	0.6	30	250
57	2500	Free Lane Selection	0.6	50	100
58	2500	Free Lane Selection	0.6	50	250
59	2500	Free Lane Selection	0.6	70	100
60	2500	Free Lane Selection	0.6	70	250

To compare the results from these scenarios certain base scenarios were created. Base case scenarios are the scenarios in which the connected vehicles are in the network but their CACC features are not activated and therefore these vehicles become regular vehicles. Their operating and emission characteristics can then be individually compared to the scenarios where CACC are activated. There are a total of eight base cases from a factorial combination of two volume levels and four levels of market penetration. Without CACC activation, the vehicles are operating as human driving using VISSIM's default driver models. Emission rates for different vehicles were obtained using the procedure mentioned in the previous section. These emission rates also serve as base cases for these connected vehicles to determine the impact when the CACC feature is activated. Table 6 shows the eight base cases which were created to form a benchmark for different scenarios of connected vehicles.

Table 6: Base Case Scenarios (15).

Scenario	Volume	% CV
Scenario_400010	4000	10
Scenario_400030	4000	30
Scenario_400050	4000	50
Scenario_400070	4000	70
Scenario_250010	2500	10
Scenario_250030	2500	30
Scenario_250050	2500	50
Scenario_250070	2500	70

5.3 Data Collection

The simulation period was one hour fifteen minute. First five minutes were taken as the warm up period. Also, the first one-kilometer section was excluded from the analysis as it was influenced by the new vehicle input. Different combination of factors mentioned in section 5.2 were combined together to form 60 scenarios. 4 of the combinations with CACC vehicles on left lane, 4000 vehicle/hour volume and seventy percent market penetration rate were removed from evaluation. This was done because the flow rate on left lane for these four scenarios exceeded 1800 vehicles/hour. A higher flow rate would have reduced the speed and caused oversaturated flow. In total 60 scenarios were evaluated. Apart from these 60 scenarios, 8 more scenarios for base case were evaluated.

A data collection point was placed in the middle of the section to get data on headway, speed and acceleration. A sample output from the data collection point is shown in Table 7.

In addition, two different files were generated from the external driver model DLL. One file was used to record vehicle trajectory data and packet drop data. Table 8 shows a sample data from this file. This file contained data for all the vehicles in the network at one second time interval. In order to increase the simulation speed, the data were logged at every 300 seconds. This file contained control data such as vehicle speed, acceleration and distance from the leader and follower. This data also had a reception column which contained information regarding signal drop. A value of one for reception means that the ego vehicle successfully received the packets from the leader is a particular time step and zero means that there was a signal drop in that time step. A value of -99 means that the vehicle is not in platooning mode and thus this column is not relevant. This file was used calculate the emissions for CACC equipped vehicles.

Table 7: Selected Data from Data Collection Point (15).

LaneNo.	Entry Time	Exit Time	VehNo	Vehicle type	v[mph]	acc[ft/s2]	VehLength[ft]
1	695.08	-1	1	100	73.4	0	12.3
1	-1	695.19	1	100	73.4	0	12.3
2	726.16	-1	2	100	70.3	0	12.3
2	-1	726.28	2	100	70.3	0	12.3
1	730.28	-1	16	100	72.3	0	15.24
1	-1	730.43	16	100	72.3	0	15.24
1	733.33	-1	14	100	71.8	0	13.16
1	-1	733.46	14	100	71.8	0	13.16
3	733.48	-1	8	100	70.7	0	12.3
3	-1	733.6	8	100	70.7	0	12.3
1	734.44	-1	6	100	72.6	0	15.12
1	-1	734.58	6	100	72.6	0	15.12
3	734.66	-1	15	100	71.2	0.82	15.12
3	-1	734.8	15	100	71.3	0.82	15.12
3	735.87	-1	26	100	70.4	2.11	15.62
2	736.08	-1	5	100	69.7	0	15.62

Table 8: Output from External Driver Model DLL for Vehicle Trajectory (15).

vehID	simtime_sec	speed_mph	acc_fps2	status	front_gap_ft	rear_gap_ft	Reception
351	342	63.489	-0.45	201	222.59	323.56	-99
351	343	63.232	-0.32	201	219.37	325.54	-99
351	344	63.053	-0.22	201	216.79	327.03	-99
351	345	62.938	-0.13	201	214.76	327.45	-99
351	346	62.878	-0.057	201	213.18	326.89	-99
351	347	62.862	0.0025	201	211.97	325.43	-99
355	347	63.256	0.00056	201	150.41	282.59	-99
351	348	62.882	0.05	201	211.08	323.12	-99
355	348	63.256	0.00037	201	152.15	282.65	-99
351	349	62.931	0.087	201	210.45	320.89	-99
355	349	63.256	0	201	153.87	282.71	-99
358	349	63.222	0.009	201	215.7	232.97	-99
351	350	63.257	1	203	209.95	319.67	1
355	350	63.256	0	201	154.73	282.76	-99
358	350	63.228	0.0075	201	215.75	228.73	-99
351	351	63.287	-0.63	201	209.13	319.91	-99

6 RESULTS

In this section the author discusses the impact of platooning in a connected vehicle environment on freeway performance. Many of the previous studies have shown that platooning can increase traffic flow rate thus it is selected as one of the performance measure that is evaluated in this study. Close spaced platoons reduce the wind drag experienced by the vehicles in the platoon. This in turn reduces the total emission of a vehicle. A detailed analysis of how different factors affect emissions is provided in this section.

6.1 Traffic Flow

Traffic flow rate for five minute intervals were computed from the headway data obtained from data collection points. The maximum flow rate for different combination of volume, MPR of CACC and lane settings were computed. The maximum throughput for a particular scenario was estimated by using maximum flow rate. Table 9 show the flow rate summary. In all of the cases the maximum flow exceeds the input volume. A maximum flow rate of 4970 vehicles per hour is obtained when there is a dedicated lane of CACC left lane and MPR of CACC in 50% and Volume is 4000 vehicles. An important point to note here is that all the CACC equipped vehicles are trucks thus a volume of 4970 vehicles/hour represents a significant increase in flow rate.

Table 9: Flow Rate Summary.

Volume	% CV	Lane Setting	Max Flow Rate
2500	10	CACC Left Lane	2854.86
2500	10	Free Lane Selection	2819.72
2500	30	CACC Left Lane	2935.77
2500	30	Free Lane Selection	2831.62
2500	50	CACC Left Lane	3128.64
2500	50	Free Lane Selection	2890.15
2500	70	CACC Left Lane	2976.10
2500	70	Free Lane Selection	2900.62
4000	10	CACC Left Lane	4632.77
4000	10	Free Lane Selection	4631.16
4000	30	CACC Left Lane	4647.76
4000	30	Free Lane Selection	4567.28
4000	50	CACC Left Lane	4969.99
4000	50	Free Lane Selection	4860.53
4000	70	Free Lane Selection	4775.98

Figure 5 presents the mean and maximum flow rate for different combination of volume, market penetration rate. The maximum flow rate increases as the MPR of CACC increases till 50%. There is a drop in flow rate when the MPR of CACC increases further to 70%.

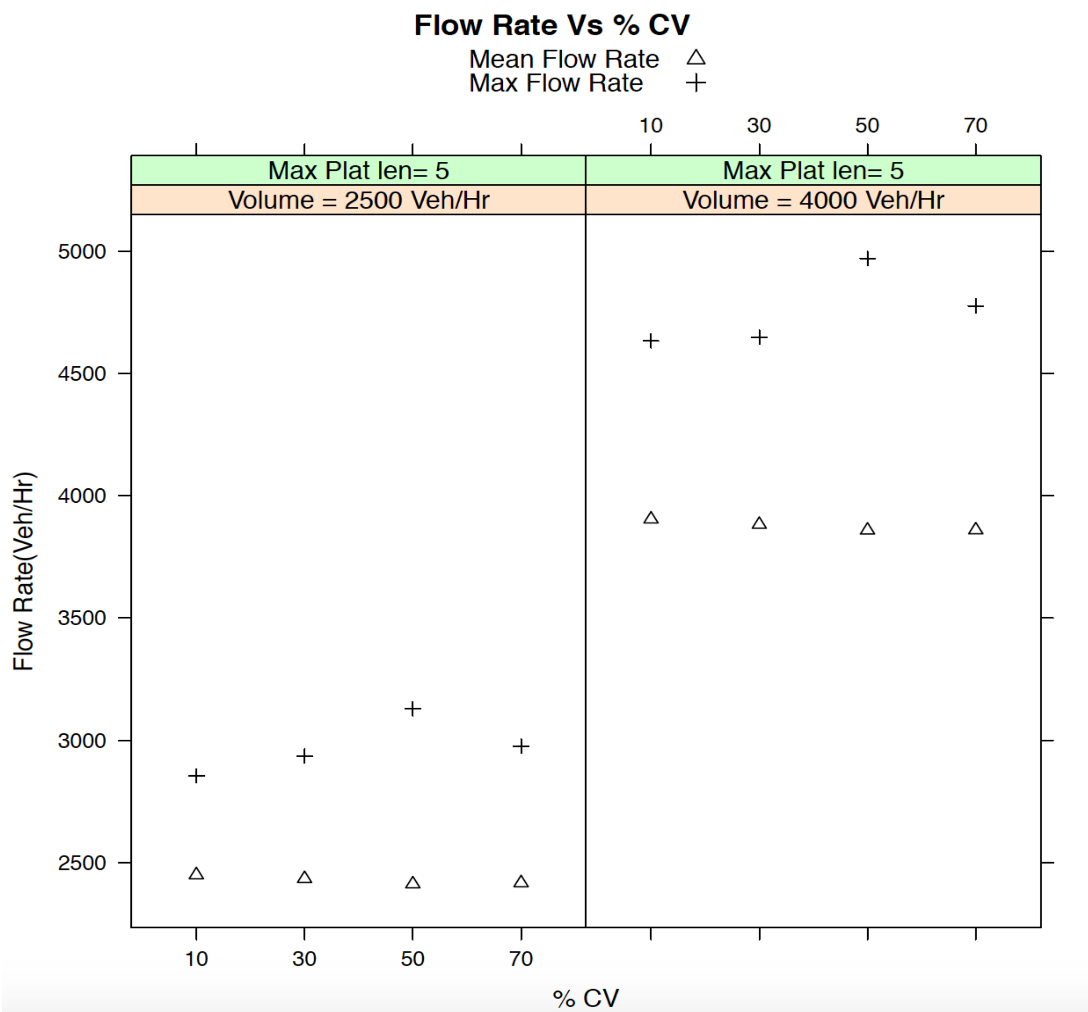

Figure 5: Mean and Maximum Flow Rates for Different Scenarios

6.2 Environmental Impact

As discussed before truck platooning can reduce emissions. In this study we have analyzed the impact of truck platooning on emission with respect to different factors such as market penetration rate, improper wireless communication and lane restriction policies. Emission rates for different pollutant such as CO_2, CO, HC and NO_x were evaluated for different factors. Emission results for only CO_2 are presented here since these pollutants showed similar trends. Also, the fuel consumption rate depends on CO_2, CO and HC based on the carbon balance equation and thus would follow similar trend as CO_2. Figure 6 presents a box plot of percent change in CO_2 for different desired gap setting. It can be seen that for smaller desired gap the reduction CO_2 compared with the base case has lower median and 1st and 3rd quartile values.

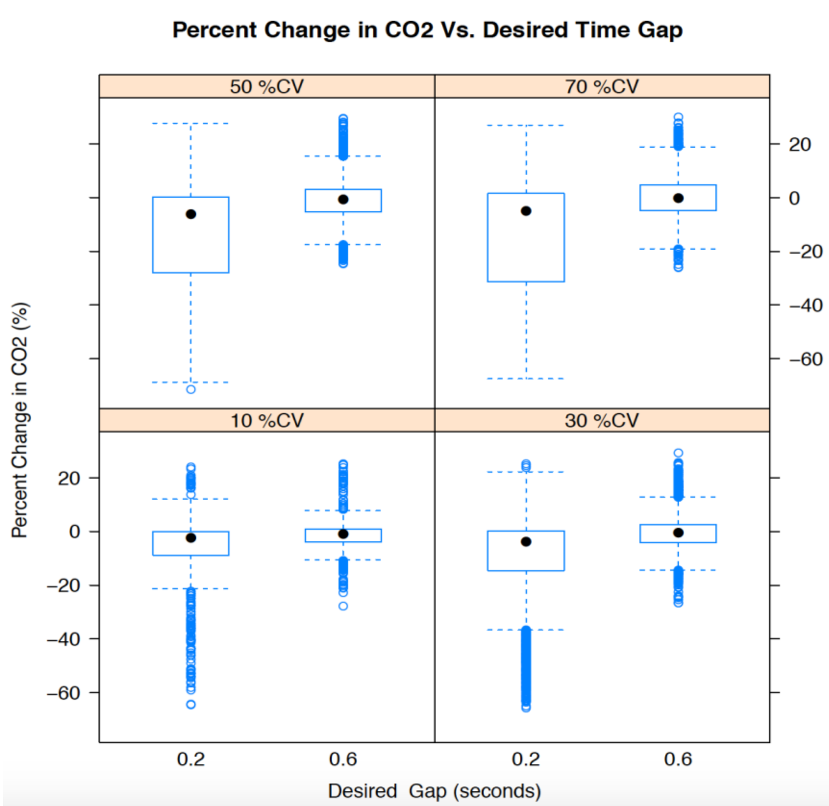

Figure 6: Percent Change in CO_2 vs. Desired Gap.

Figure 7 shows how the mean percent reduction in CO_2 is affected by desired gap. It can be seen that for certain combination of factors and a desired gap of 0.6 seconds, there is no reduction in CO_2 compared with the non connected vehicle environment.

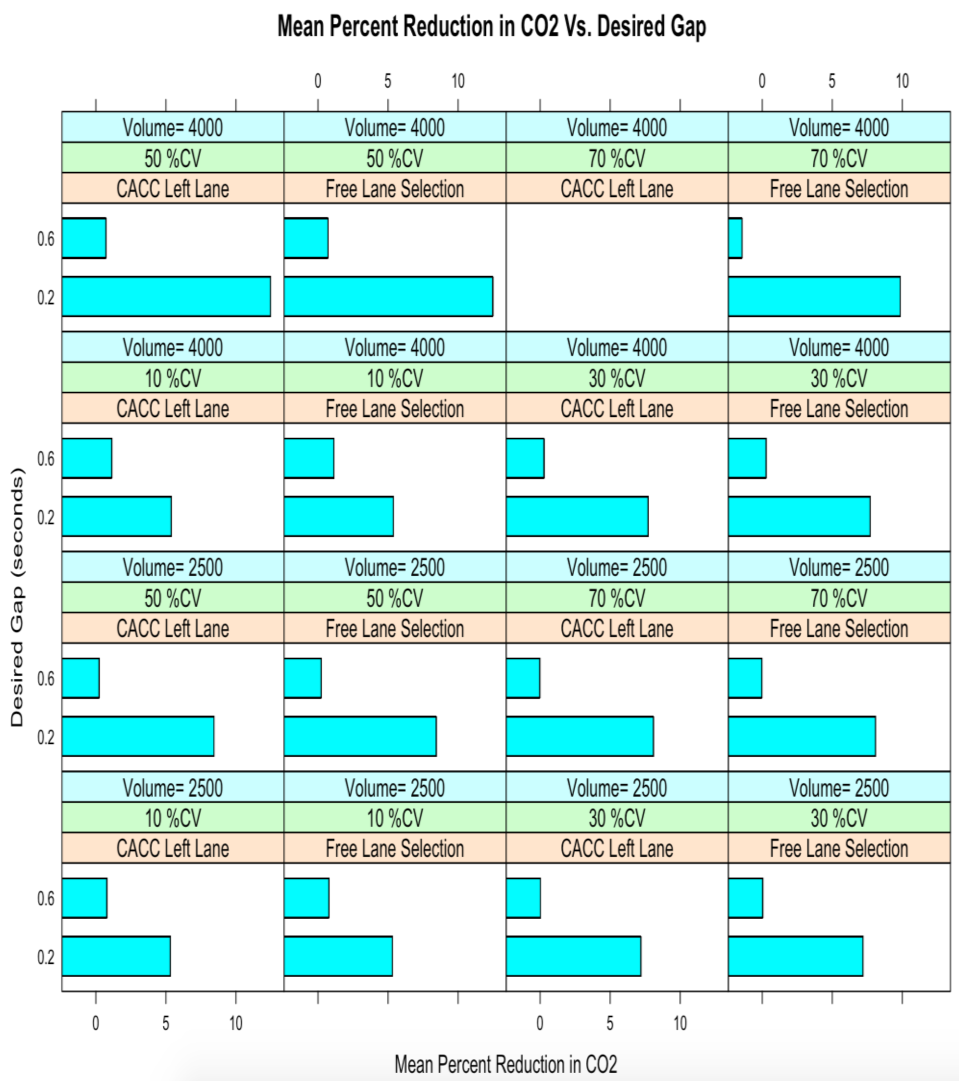

Figure 7: Mean Percent Reduction in CO_2 vs. Desired Gap.

Figure 8 shows how lane change policy effects the reduction in CO_2 .A dedicated lane for CACC is beneficial in reducing emissions in all the cases. . This is because the probability of platoon formation increases when all the CACC equipped vehicles are in one lane.

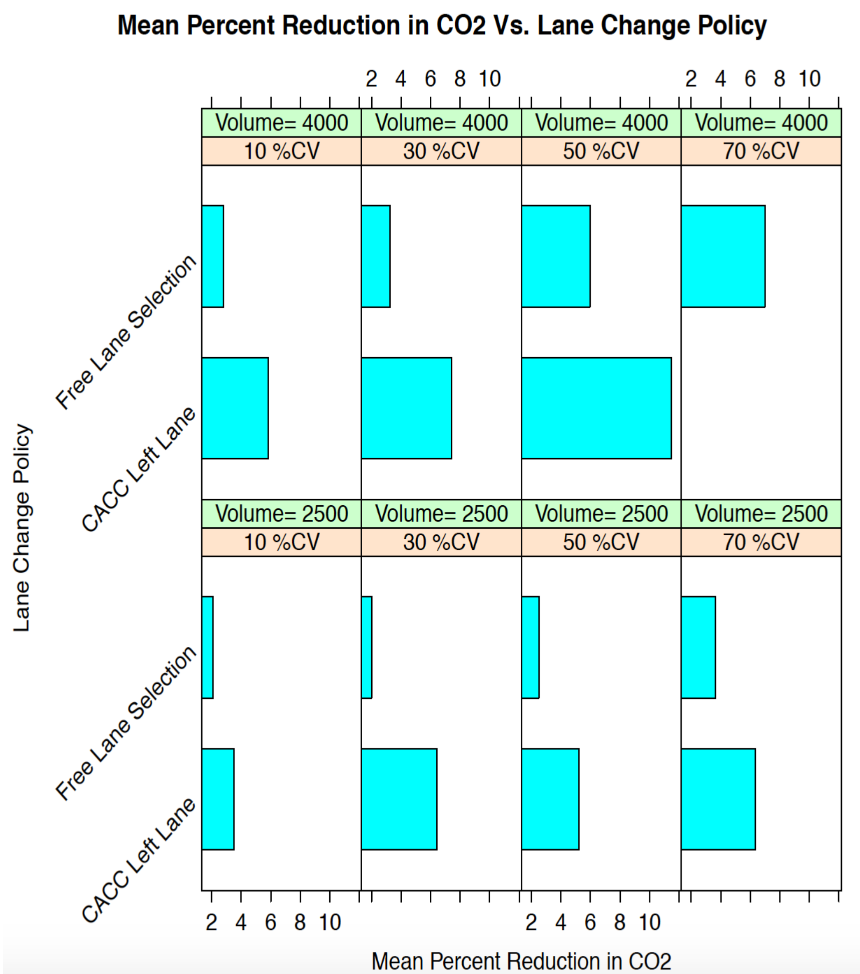

Figure 8: Mean Percent Reduction in CO_2 vs. Lane Change Policy.

Figure 9 shows how wireless communication effects the CO_2 emissions. A transmission power of 100 meters represents bad communication and 250 meters represents good communication. It was seen the emission benefits are more for bad communication.

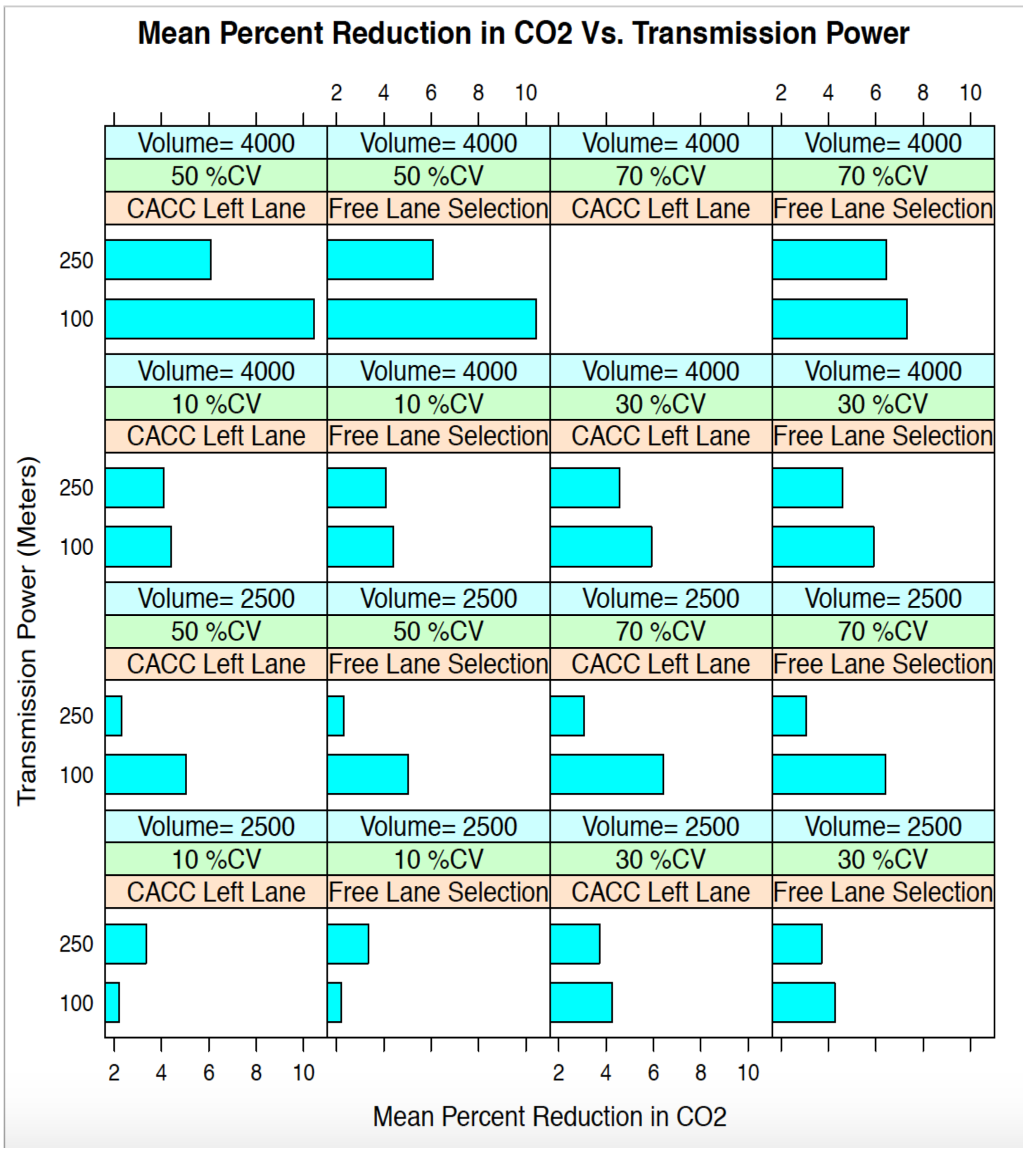

Figure 9: Mean Percent Reduction in CO_2 vs. Transmission Power.

More emission benefits are seen for bad wireless communication because the overall speed of vehicles in bad communication cases were lower than the speed in good communication cases. This difference in speed reduced the power requirement thus giving lower emissions for bad communication scenarios. Figure 10 and Figure 11 show the different in speed for CV environment compared to the base case environment.

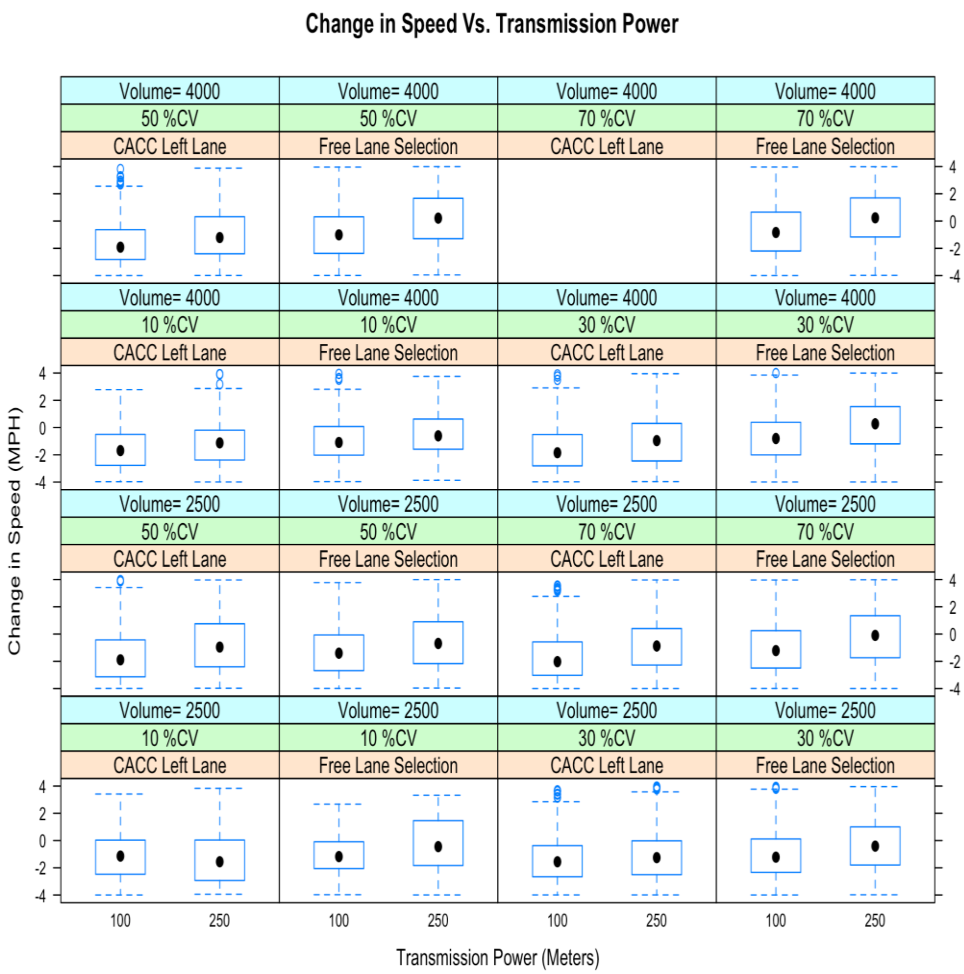

Figure 10: Change in Speed vs. Transmission Power.

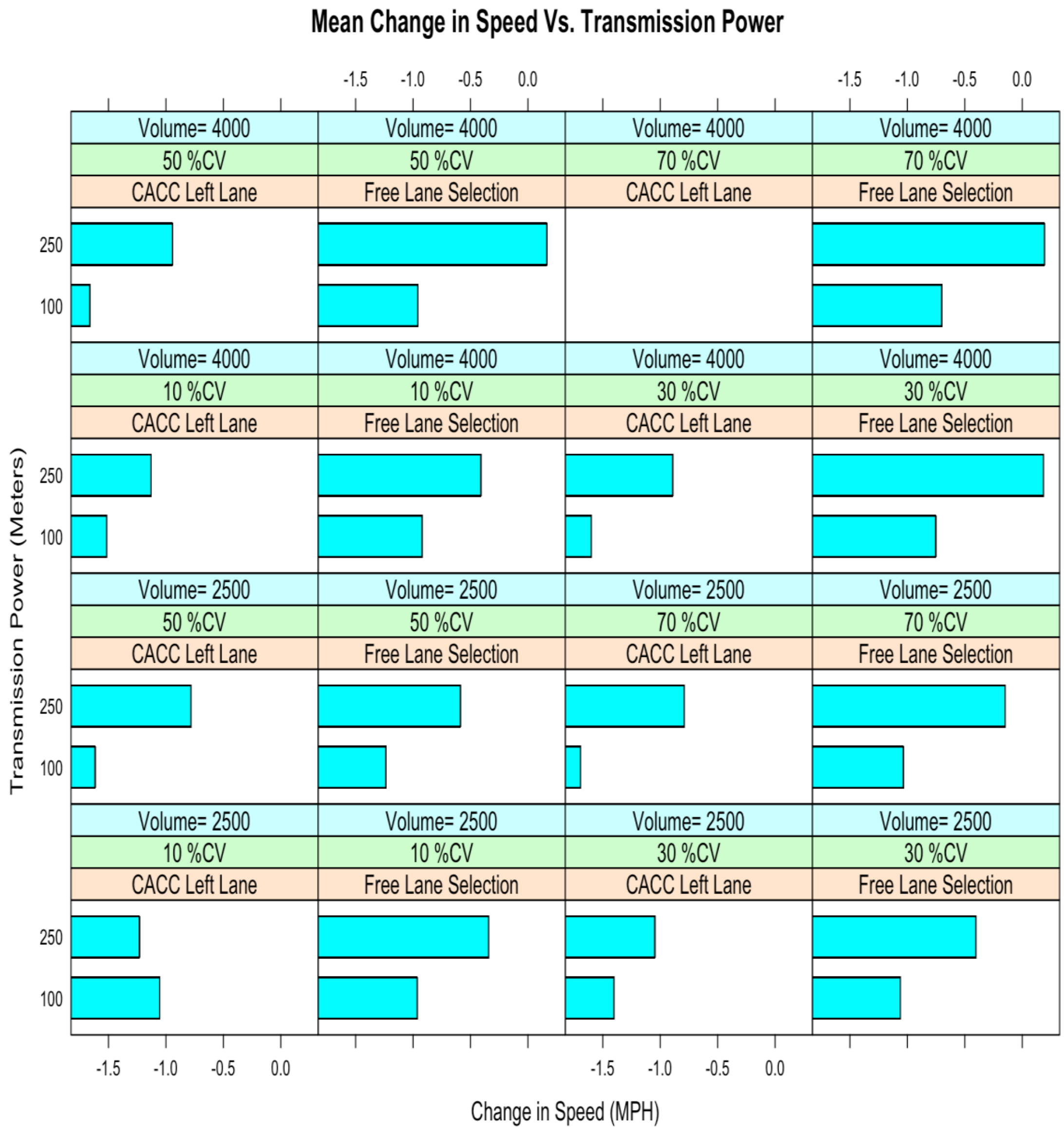

Figure 11: Mean Change in Speed vs. Transmission Power.

Figure 12 shows how average front gap effects the CO_2 emissions in CV environment. Average front gap here is calculated for only when the vehicles are in platooning mode.

It can be seen that for lower front gap the CO_2 emissions are less. This is because wind drag reduces as average front gap reduces between two vehicles in a platoon.

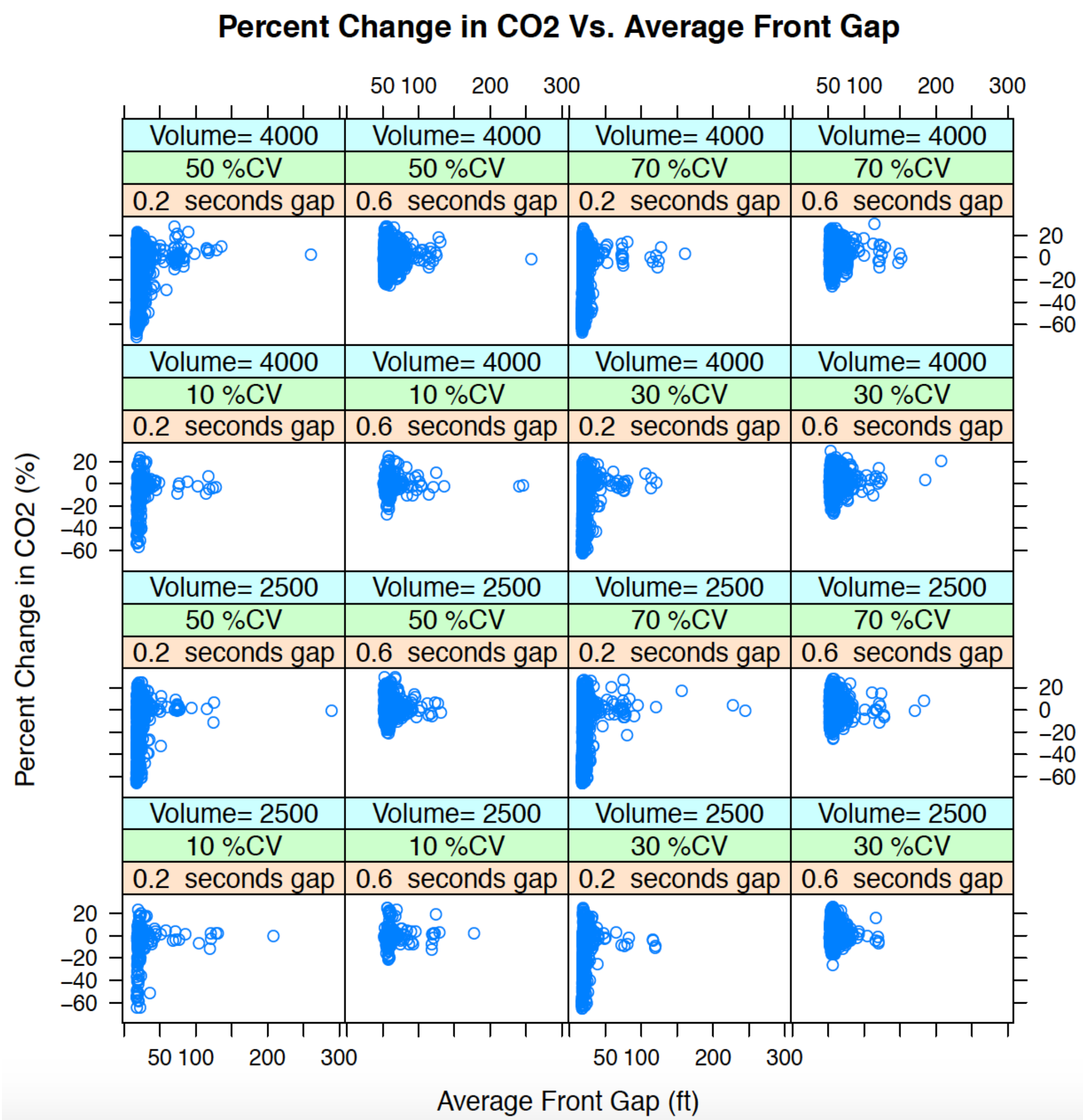

Figure 12: Percent Change in CO_2 vs. Average Front Gap.

Figure 13 shows how change in speed in CV environment as compared to non CV environment effects the percent change in CO_2. It can be seen that if the speed in CV environment is less than the speed in non CV environment then there is a decrease in emissions This is because more power is consumed to maintain higher speed.

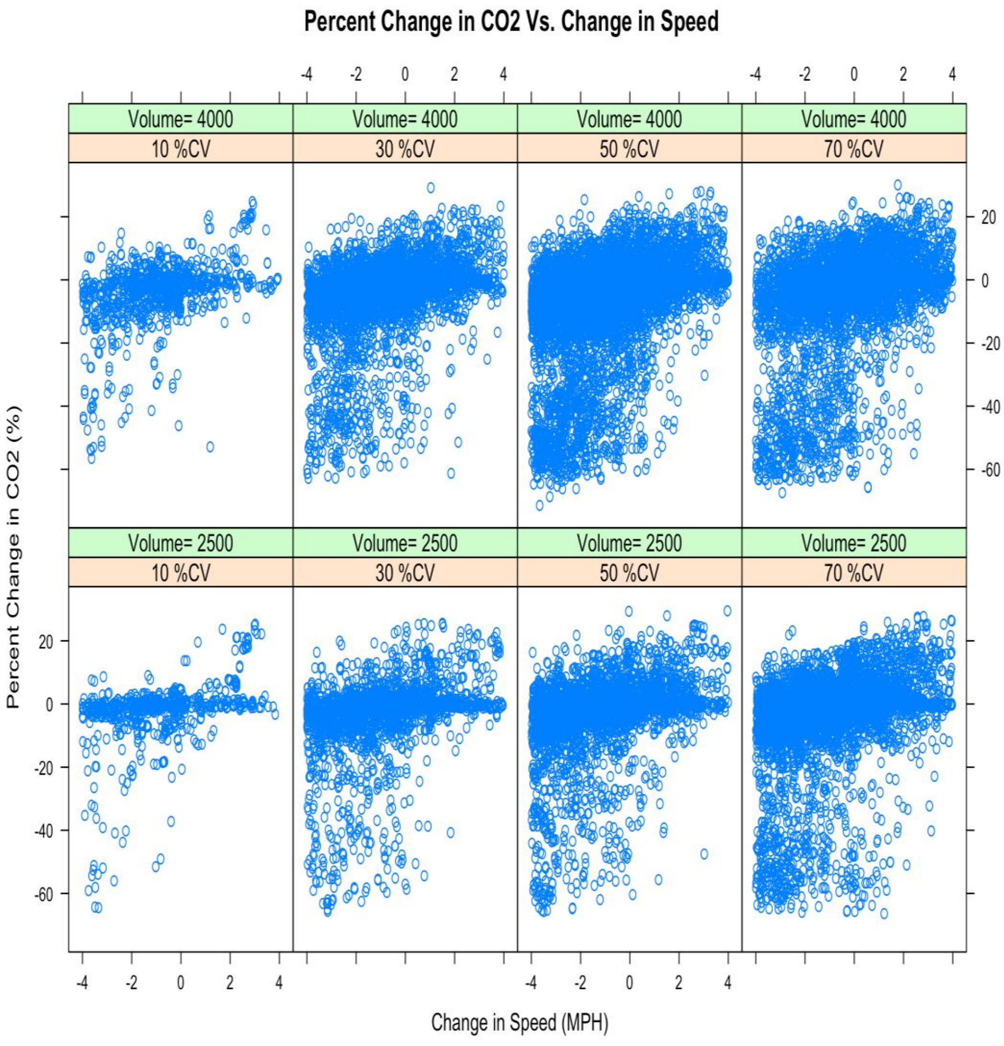

Figure 13: Percent Change in CO_2 vs. Speed Difference.

Table 10 shows the result of Tukey's HSD test on percent reduction in CO_2 for a truck in connected vehicle environment as compared to non-connected vehicle environment. Mean percent reduction in CO_2 is compared across different level of Volume, MPR of CACC, desired gap and lane change settings. Means with the same letter in group column are not significantly different.

Table 10: Summary of Tukey's HSD Test.

S.No	Volume (veh/hour)	MPR of CACC (%)	Desired Gap (sec)	Lane Change Setting	Mean reduction in CO_2	Group
1	2500	70	0.6	Free Lane Selection	0.887	a
2	2500	50	0.6	Free Lane Selection	0.746	a
3	2500	30	0.6	Free Lane Selection	0.350	a
4	4000	70	0.6	Free Lane Selection	0.181	a
5	2500	50	0.6	CACC Left Lane	0.103	a
6	2500	10	0.6	CACC Left Lane	-0.144	ab
7	2500	30	0.6	CACC Left Lane	-0.244	ab
8	4000	50	0.6	Free Lane Selection	-0.459	ab
9	4000	30	0.6	Free Lane Selection	-0.464	ab
10	2500	70	0.6	CACC Left Lane	-0.505	ab
11	2500	10	0.6	Free Lane Selection	-0.757	ab
12	4000	30	0.6	CACC Left Lane	-0.964	ab
13	4000	10	0.6	Free Lane Selection	-1.197	ab
14	4000	10	0.6	CACC Left Lane	-1.913	ab
15	4000	50	0.6	CACC Left Lane	-2.572	b
16	2500	10	0.2	Free Lane Selection	-3.504	bc
17	4000	10	0.2	Free Lane Selection	-4.589	bc
18	2500	30	0.2	Free Lane Selection	-4.622	bc
19	2500	50	0.2	Free Lane Selection	-6.388	c
20	4000	30	0.2	Free Lane Selection	-6.530	c
21	2500	10	0.2	CACC Left Lane	-7.213	cd
22	2500	70	0.2	Free Lane Selection	-9.339	d
23	4000	10	0.2	CACC Left Lane	-10.372	de
24	2500	50	0.2	CACC Left Lane	-11.445	de
25	4000	50	0.2	Free Lane Selection	-12.614	e
26	2500	30	0.2	CACC Left Lane	-13.296	ef
27	2500	70	0.2	CACC Left Lane	-15.127	fg
28	4000	30	0.2	CACC Left Lane	-15.208	fg
29	4000	70	0.2	Free Lane Selection	-16.340	g
30	4000	50	0.2	CACC Left Lane	-23.208	h

We fail to reject the null hypothesis that groups means of percent reduction in CO_2 is different at 95% significance level for majority of the groups with a desired gap of 0.6 seconds. Also, smaller desired gap results in more emission benefits as the wind drag reduction for smaller gap is more. Dedicated lane can provide more emission benefits at lower MPR of CACC as compared to free lane selection policy at higher MPRC of CACC. High volume with a MPR of CACC at 50% and a dedicated lane for CACC and a desired gap of 0.2 seconds provides the most emission benefit. The percent reduction in CO_2 at this level is significantly different from all other groups listed in Table 10.

In order to get an idea of the emission benefits of CACC system for a particular vehicle a regression model was fitted for percentage change in CO_2 with the parameters that can be controlled or predicted before starting a trip. The results of the regression model are presented in Table 11. The R^2 value for this model is 0.287.

Table 11: Regression Coefficient Estimate for Predicting Percent Change in CO_2.

Coefficients	Estimates	Std. Error	t value	p value
Intercept	-6.868	0.372	-18.419	$<2e^{-16}$
Speed difference (Mph)	3.017	0.046	65.743	$<2e^{-16}$
Percent time spent as follower	-0.0412	0.004	-11.571	$<2e^{-16}$
Lane change setting=Free lane selection	0.971	0.178	5.452	$5.03e^{-08}$
Desired gap= 0.6 seconds	11.746	0.178	65.994	$<2e^{-16}$

Following are the salient points:

- The coefficient of percent of time spent as a follower is negative thus more time a vehicle spends as a follower the more reduction in CO_2 will occur.
- There is an increase of 3.01 percent in percent change of CO_2 when the average speed of a vehicle in CACC mode is 1 Mph greater than the speed of the same vehicle without CACC. It takes more power to maintain higher speed which reduces the emission benefit.
- When all CACC equipped vehicles are on left lane more reduction in CO_2 is observed as compared to the free lane selection mode.
- There is a huge reduction in CO_2 when platoon members maintain smaller gaps.

7 CONCLUSIONS

In this study the author developed a mechanism to use data from simulated connected vehicles to obtain various freeway performance measures. The author developed lane change logics and platooning logics for CACC equipped vehicles. The author coded the driver model and platooning model for CACC equipped vehicles in the VISSIM external driver model API. VISSIM external driver model API calculated and sent the values of control related parameters such as acceleration to VISSIM at each time step and for all the CACC equipped vehicles in the network. The author also developed a methodology to reduce the output from VISSIM so that patterns between different variables could be established. Moreover, the author analyzed the effect of volume, market penetration rate of CACC, wireless communication, lane restriction policies, and desired gap on freeway performance measures such as flow rate and emissions. A regression model was fitted to explain the change in emissions with respect to certain measurable variables. Following are the important findings from the research:

- Left lane restriction for CACC can result in a maximum flow rate of 4970 vehicles/hour for a volume of 4000 and 50% MPR of CACC. Lane restriction promotes platoon formation, which increases flow rate.
- Good communication helps increase the speed of CACC equipped vehicles. Good communication results in more stable platoons which do not break often and maintain constant speed for long duration.

- Since vehicles in good communication cases generally have higher speed as compared to bad communication cases with all other factors being equal, the emission benefits in good communication cases are lower than the bad communication cases.
- At lower average speed the emission benefits are more. Lower speed has smaller emission rate in the MOVES model given all other factors are fixed.
- An increase in market penetration rate of CACC results in an increase in reduction of emissions at a desired gap of 0.2 seconds.
- Left lane restriction for CACC can result in lower emission. This is because a dedicated lane for CACC promotes platoon formation.

7.1 Future Recommendations

Following are the recommendation for future work:

- This research does not consider the merging, diverging and weaving freeway sections. Incorporating these would give a more detailed impact of connected vehicle environment on freeway performance.
- In this study only platoon formation logics were developed and implemented. In future, algorithm can be developed for platoon dissociation scenarios. This algorithm can handle scenarios such as platoon member exiting the freeway.

- The platoon formation model can be modified so that CACC equipped vehicles can actively seek other CACC equipped vehicles and change lane to form platoons.

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